The turbulence between geomechanics and vibroacoustics: what is common point?

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Outline of the speech

Three main parts.

Each corresponds to a work that was made possible under Fabien's impetus

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1. Erosion of a cohesive soil by turbulent flow (IRPHE-IRSTEA)
2. Acoustic emission of a turbulent flow in a soil (IRPHE-IRSTEA-LMA)
3. Singing risers (IRPHE-LMA)

Part 1

Erosion of a cohesive soil by turbulent flow

Stéphane Bonelli

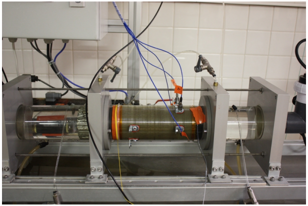
Part 2

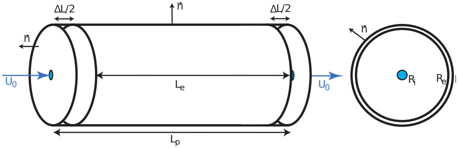
Acoustic emission of a turbulent flow in a soil

Stéphane Bonelli and Pierre-Olivier Mattei

Simplified model for a soil experimental model - PhD thesis Ch. Jeanniot

Let's consider a cylindrical sample of soil of radius R_e and length L_e, pierced in its center by a cylindrical hole of radius R_i. This sample is embedded in a housing of radius R_p and length L_p.





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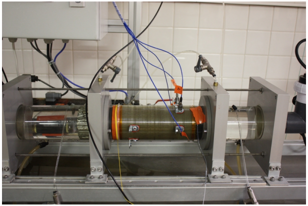

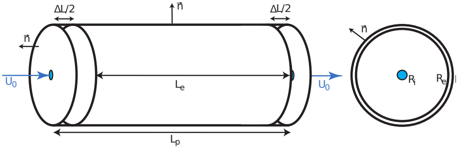

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- Can we measure at the surface of the housing the sound pressure created by the inner flow ?

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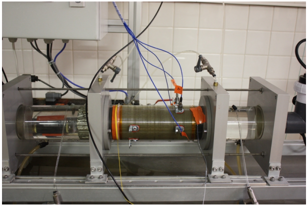

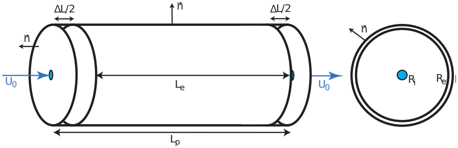

This sample is excited by a turbulent flow that passes trough the inner hole.

- Can we measure at the surface of the housing the sound pressure created by the inner flow ?
- is it possible to quantify the inner flow/inner hole ?

Simplified model for a soil experimental model - Cont'd

The acoustic pressure $p(M)$ inside the soil is solution of

$$\begin{aligned}\left[\Delta - \imath\eta\frac{\omega}{c_0^2} + \frac{\omega^2}{c_0^2}\right] p(M,\omega) &= S(M',\omega), M, M' \in]0,R_e]\times]0,L_p] \\ p(M,\omega) &= 0, x=0, x=L_p \text{ soft boundary} \\ \partial_n p(M,\omega) &= 0, r=R_p \text{ rigid boundary}\end{aligned}$$

η is the viscous damping of the soil and $S(M,,\omega)$ is the forcing term.

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Because of the simplified geometry, $P(M)$ can be expressed as a sum of normal modes $\Psi_{mns}(M) = A_{mns}\exp(\imath m\theta)\cos(n\pi x/L_p)J_m(\kappa_{ms} r)$ where $J'_m(\kappa_{ms}R_p) = 0$:

$$p(M,\omega) = \sum_{mns}^{\infty} \frac{\langle S(M',\omega), \Psi_{mns}(M')\rangle \Psi_{mns}(M)}{A_{mns}\left(\omega^2 - \imath\eta\omega - {\omega_{mns}}^2\right)}$$

$\omega_{mns}^2 = c_0^2\left(\kappa_{ms}^2 + \left(\frac{n\pi}{2L_p}\right)^2\right)$: resonances of the soil sample

Simplified model for a soil experimental model - Cont'd

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$\omega_{mns}^2 = c_0^2\left(\kappa_{ms}^2 + \left(\frac{n\pi}{2L_p}\right)^2\right)$: resonances of the soil sample

As $\kappa_{0,0} = 0$, the first two resonances $f_{mns} = \omega_{mns}/(2\pi)$ of this system are given by $f_{0n0} = c_0 \times n/(2L_p), n = 1, 2,$ with $c_0 = 1500$ m/s and $L_p =$ m:
$f_{010} \approx 2500$ Hz and $f_{010} \approx 5000$ Hz

Simplified model for a soil experimental model - Cont'd

Now, if the flow inside the soil sample is turbulent, it can be described by a Corcos model which power spectral density of the excitation is given by

$$\Phi_S(Q, Q', \omega) = \Phi_0(\omega) \exp\left(\frac{-R_i|\theta - \theta'|}{L_\theta(\omega)}\right) \exp\left(\frac{-|x - x'|}{L_x(\omega)}\right) \exp\left(\frac{\imath\omega(x - x')}{U_c(\omega)}\right)$$

$L_x(\omega)$, $L_\theta(\omega)$ and $\Phi_0(\omega)$ are parameters given in the literature

Simplified model for a soil experimental model - Cont'd

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The variable separation in both the Corcos model and pressure field allows analytical expression for the power spectral density of the pressure inside the soil sample given by linear combination of Bessel and trigonometric functions

$$\begin{aligned}\Phi_p(M,M';\omega) &= \Phi_0(\omega)\sum_{m=-\infty}^{\infty} I_{\theta m}(L_\theta,R_i)\\ &\times\sum_{n,s,\nu,\sigma}\frac{J_m(\kappa_{ms}r)J_m(\kappa_{ms}R_i)J_m(\kappa_{m\sigma}r')J_m(\kappa_{m\sigma}R_i)}{A_{mns}A_{m\nu\sigma}\left(\omega^2-\imath\eta\omega-\omega_{mns}^2\right)\left(\omega^2-\imath\eta\omega-\omega_{m\nu\sigma}^2\right)}\\ &\times\cos\left(\frac{n\pi x}{L_p}\right)\cos\left(\frac{\nu\pi x'}{L_p}\right)I_n^\nu(L_x,U_c)\exp(\imath\theta-\theta')\end{aligned}$$

$I_{\theta m}(L_\theta,R_i)$ and $I_n^\nu(L_x,U_c)$ are trigonometric functions (a few lines length...).

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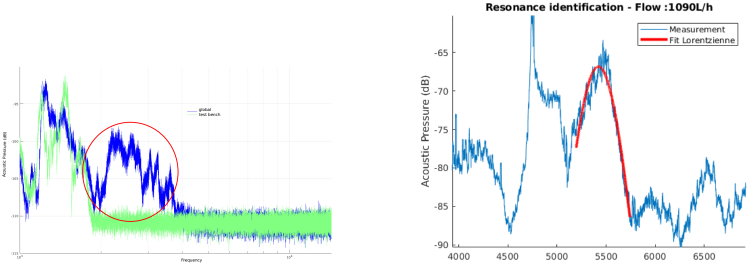
$I_{\theta m}(L_\theta,R_i)$ and $I_n^\nu(L_x,U_c)$ are trigonometric functions (a few lines length...).

By inverting the power spectral density of the pressure, it is possible (not so easy indeed) to obtain U_c and R_i.

Simplified model for a soil experimental model - Cont'd

First experimental results



Characteristic signal (left): above 1 kHz, Peak identification (right) by fitting a Lorenztian function.

Simplified model for a soil experimental model - Cont'd

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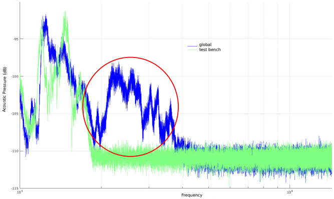
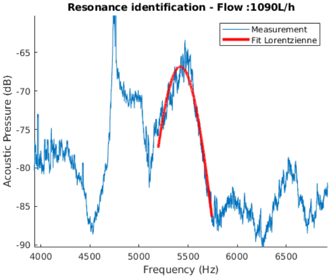
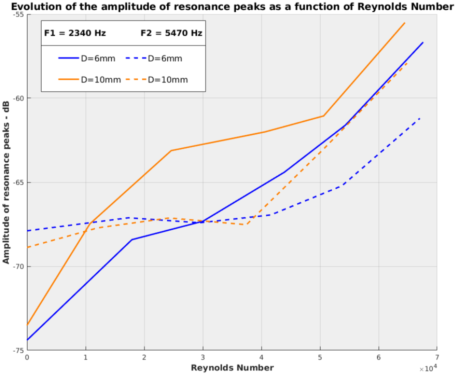




Characteristic signal (left): above 1 kHz, Peak identification (right) by fitting a Lorenztian function.

Peaks at 2340 Hz and 5470 Hz (close to those predicted)

Simplified model for a soil experimental model - Cont'd



Evolution of the two resonances when Reynolds varies

Simplified model for a soil experimental model - Comments

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- Similar models for real dikes ?

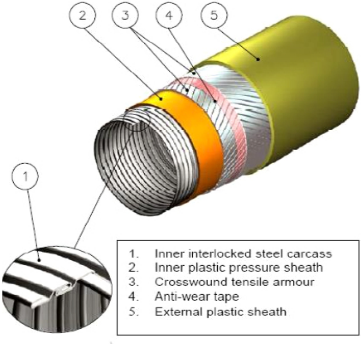
Part 3

Singing risers

Pierre-Olivier Mattei

Singing risers: introduction

- Under particular flow conditions, a corrugated pipe can “sing”: applications in music (voice of the dragon) or in industry (singing risers/FLow Induced Pulsation).



1. Inner interlocked steel carcass
2. Inner plastic pressure sheath
3. Crosswound tensile armour
4. Anti-wear tape
5. External plastic sheath

- Noise on the platform : 110 dB
- Noise inside the pipe : 160 dB (vibration and fatigue issue for adjacent equipment)
- Flow rate limitation

Singing risers: two experiments

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   Dedicated vein + microphones + hot wire probe + fast camera

   - origin of the whistling
   - one or more noise sources
   - at which localization(s)
   - weak of strong aeroacoustic coupling ?
   - what effect of the LF modulation?

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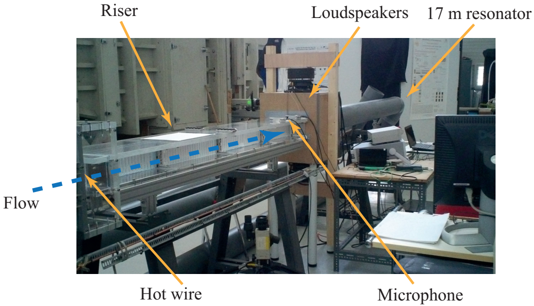
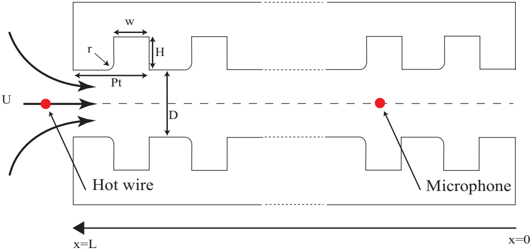
2. FLIP measurement using industrial riser

   “industrial riser” + high speed flow / high pressure + microphones + hot wire probe

   - influence of flow speed and static pressure on the FLIP onset
   - one or more noise sources
   - at which localization(s)
   - weak of strong aeroacoustics coupling ?

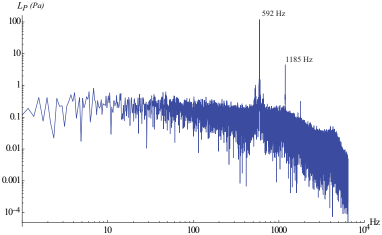
FLIP mitigation using low frequency sound - Coll. U. Kristiansen (NTNU)



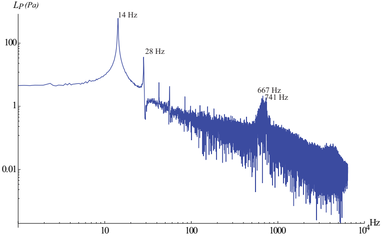


FLIP mitigation using low frequency sound - Cont'd

Sound pressure recorded inside the pipe at a flow speed of about 20 m/s.

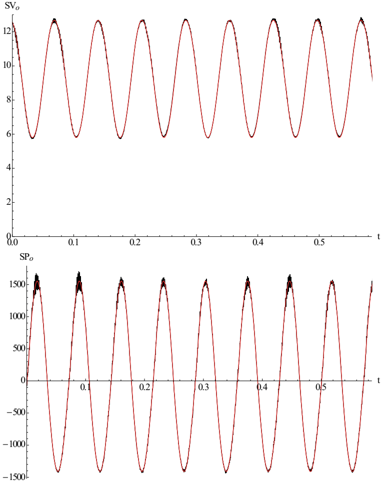


Without mitigation: maximum sound pressure of 140 *dB*



With mitigation at 14 Hz : signal 154 *dB - audible signal* 124 *dB*

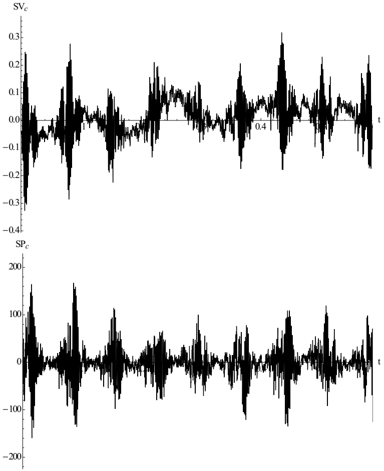
FLIP mitigation using low frequency sound - Cont'd



Time records of flow speed $SV_o(t)$ in m/s and acoustics sound pressure $SP_o(t)$ in Pa.

- One subtracts to the signal (black) the LF component and its harmonics (red)

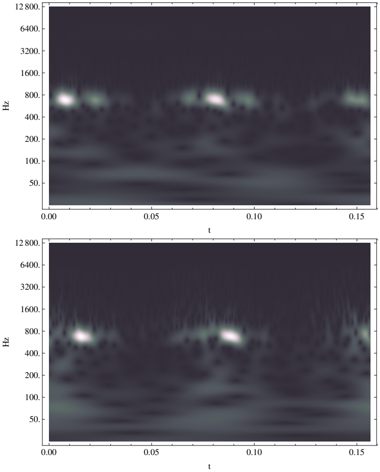
FLIP mitigation using low frequency sound - Cont'd



Fluctuations of flow speed and acoustics sound pressure.

⇒ Very strong similarity of the residues

FLIP mitigation using low frequency sound - Cont'd

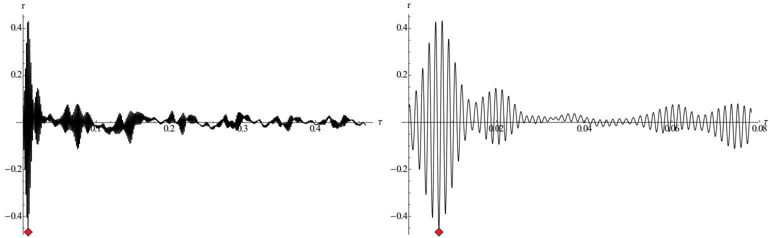


Gabor transform of flow speed and acoustics sound pressure

⇒ Shift of signals of about 0,007 s: flying time between entry and exit
⇒ Components separated by 0,014 s: round-trip flying time between entry and exit

FLIP mitigation using low frequency sound - Cont'd

Pearson's correlation between $SP_c(t)$ et $SV_c(t+\tau)$ vs τ calculated on 2^{17} samples for 6 000 time steps



$|r| = 0,5$ at $\tau = 0,0069$.

The correlation fluctuates at 669 Hz.

FLIP mitigation using low frequency sound - Comments

The analysis of experimental data showed that:

- the whistling is induced by instabilities **located at the pipe entry**

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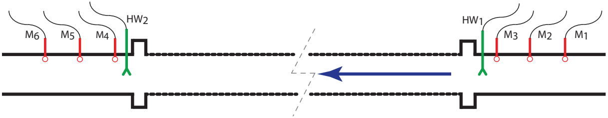
- the pressure fluctuations **propagate at sound speed**
- the pressure fluctuations **are amplified by successive reflections** at pipe exits
- the flow LF modulation **limit the emission** of pressure fluctuation
- its frequency can be **tuned to limit amplification** by reflection

FLIP measurement using industrial riser - PhD thesis G. Galeron

Experiments realized on a 18.34 m length "true" industrial riser (15.24 cm internal diameter) at CESAME test facility centre (Poitiers, France):

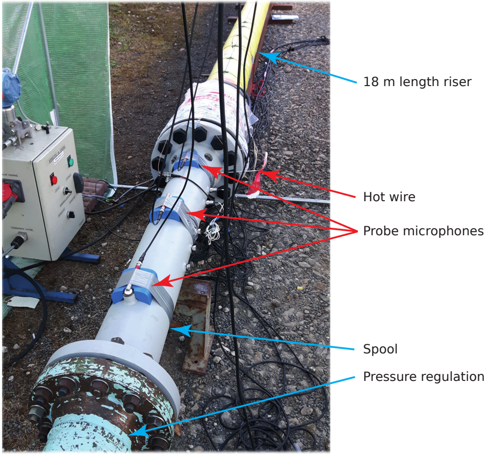
- Internal Pressure $p_i \in [1;42]$ bars
- Flow velocities $v_0 \in [5;80]$ m/s
- 6 microphone probes Gras $p_i < 6$ bars
- 4 microphones Kulite $p_i < 50$ bars
- 2 Dantec Hot wires $V_0 > 0$ m/s
- ΔP probe, thermal probe, static pressure probe



Problem geometry

FLIP measurement using industrial riser - PhD thesis G. Galeron

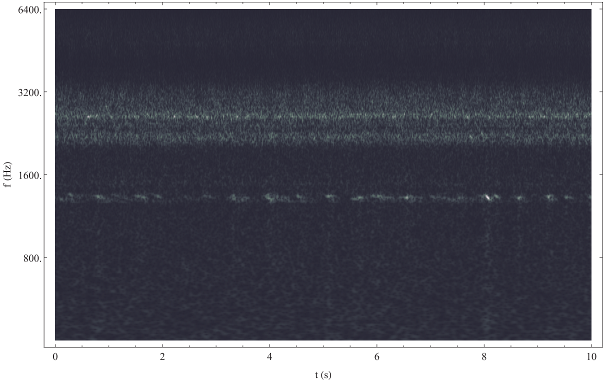
Air supplying realized through emptying of a 200 m^3 tank at 200 bars ;



Fixture photograph - downstream coupler

FLIP measurement using industrial riser - Cont'd

Example of time-frequency analysis around the maximum whistling of the riser (upstream)

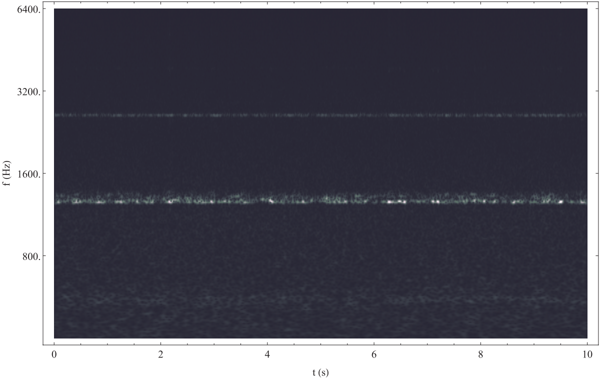


Wavelet (Gabor) transform of an upstream microphone signal

Fluctuations in time and amplitude.
Upstream signal noisy (induced by fixture air supplying).

FLIP measurement using industrial riser - Cont'd

Example of time-frequency analysis around the maximum whistling of the riser (downstream)

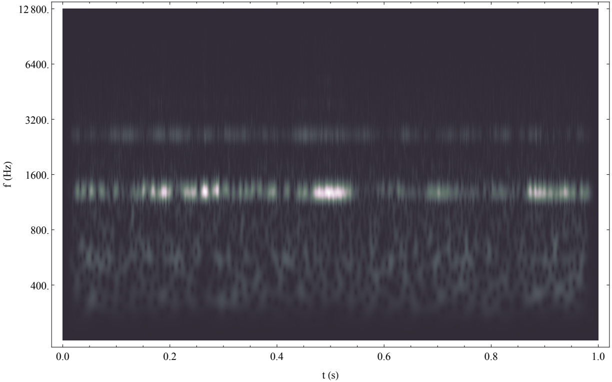


Wavelet (Gabor) transform of a downstream microphone signal

Fluctuations in time, amplitude and frequency.
Downstream signal almost free from noise. The pipe acts as a pass-band filter around its transverse resonances.

FLIP measurement using industrial riser - Cont'd

Microphones 4, 5 and 6 between 449 s and 450 s. Strong whistling (about 170 dB !).



Wavelet (Gabor) transform of the microphone 4 signal

FLIP measurement using industrial riser - Cont'd

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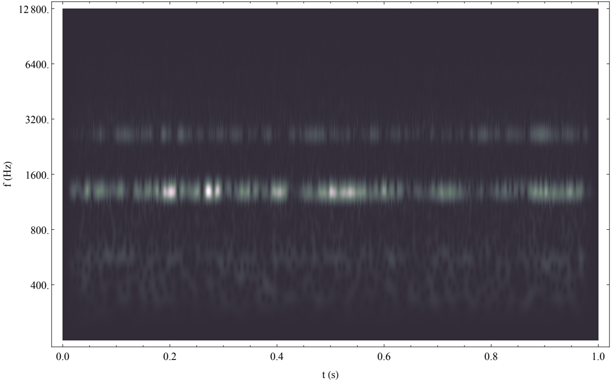
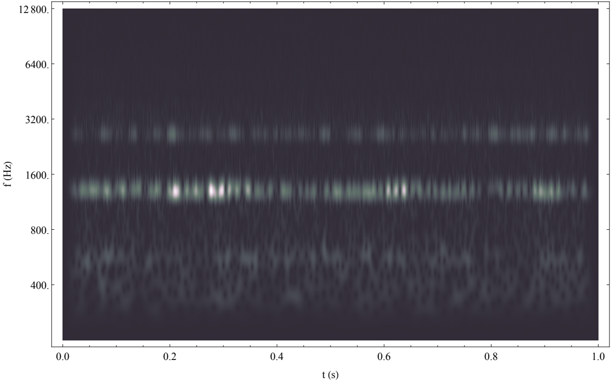


Wavelet (Gabor) transform of the microphone 5 signal

Between MG4 et MG5 ($d(MG_4; MG_5) = 0.4$ m), we estimate a time shift of about $\Delta t = 5.7$ ms, that is $L_{\Delta t}^{c_0} \approx 1.9$ m and $L_{\Delta t}^{V_0} \approx 0.39$ m

FLIP measurement using industrial riser - Cont'd

Microphones 4, 5 and 6 between 449 s and 450 s. Strong whistling (about 170 dB !).

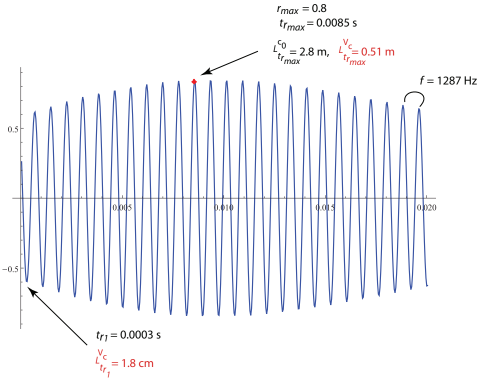


Wavelet (Gabor) transform of the microphone 6 signal

Between MG4 et MG6 ($d(MG_5; MG_6) = 0.5$ m), we estimate a time shift of about $\Delta t = 7$ ms, that is $L^{c_0}_{\Delta t} \approx 2.3$ m and $L^{V_0}_{\Delta t} \approx 0.49$ m

FLIP measurement using industrial riser - Cont'd

Correlation analysis

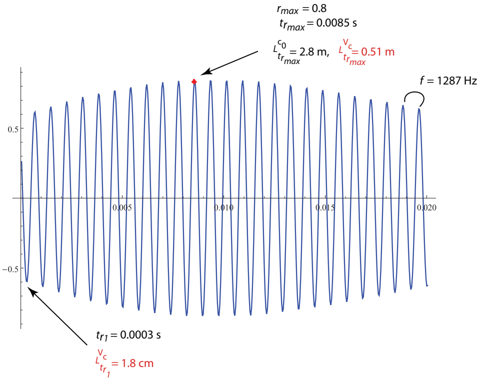


Pearson's correlation of microphones 4 and 5 ($t \in [450; 450]$ s) bandpass filtering between 800 Hz and 2000 Hz.

- 11 "oscillations" (ie 22 relative maxima) to reach the maximum correlation: $d(MG_4; MG_5) = 0.5$ m $\Rightarrow 0.4/22 \approx 2$ cm $\approx d_c$, correlation pitch

FLIP measurement using industrial riser - Cont'd

Correlation analysis



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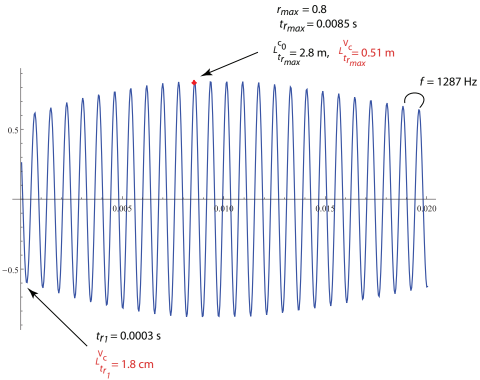
- $L^{V_c}_{t_{r_{max}}} = 0.51$ m $\approx d(MG_4; MG_5)$, $V_c = 0,7 V_{HW_2} \approx 60$ m/s

FLIP measurement using industrial riser - Cont'd

Correlation analysis



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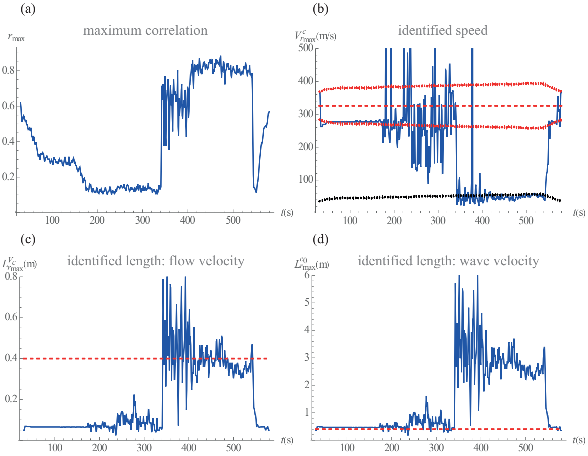
- $L^{V_c}_{t_{r_{max}}} = 0.51$ m $\approx d(MG_4; MG_5)$, $V_c = 0,7 V_{HW_2} \approx 60$ m/s
- $L^{V_c}_{t_{r_1}} = 1.8$ cm $\approx d_c$

FLIP measurement using industrial riser - Cont'd



Pearson's correlation of microphones 4 and 5
(bandpass filtering between 800 Hz and 2000 Hz.)
(a) : absolute maximum correlation r_{max}
(b) : characteristic speed $V^c_{r_{max}} = d(MG_4; MG_5)/t_{r_{max}}$
(c) : characteristic length $L^v_{r_{max}} = V_c \times t_{r_{max}}$
(d) : characteristic length $L^v_{r_{max}} = c_0 \times t_{r_{max}}$

FLIP measurement using industrial riser - Cont'd

Observations during whistling

FLIP measurement using industrial riser - Cont'd

Observations during whistling

- First correlation maximum controlled by corrugation size d_c and flow velocity

FLIP measurement using industrial riser - Cont'd

Observations during whistling

- First correlation maximum controlled by corrugation size d_c and flow velocity
- Absolute correlation maximum controlled by microphones spacing and flow velocity

FLIP measurement using industrial riser - Cont'd

Observations during whistling

- First correlation maximum controlled by corrugation size d_c and flow velocity
- Absolute correlation maximum controlled by microphones spacing and flow velocity
- Characteristic velocity at maximum correlation is that of the flow : pseudo-noise

FLIP measurement using industrial riser - Cont'd

Observations during whistling

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Conclusions

FLIP measurement using industrial riser - Cont'd

Observations during whistling

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Conclusions

- Inside a corrugated pipe, when a gas flows, the fluctuating pressure is a combination of the acoustic field at frequencies close to the internal resonances of the pipe and of the pseudo-noise induced by turbulence

FLIP measurement using industrial riser - Cont'd

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FLIP measurement using industrial riser - Cont'd

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- During whistling, the pseudo-noise spectrum is dominated by frequencies around that of the internal acoustics resonances

Last but not least

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Many thanks to you, Fabien, for making possible all this work